The Diffuse Supernova Neutrino Background

Sonia El Hedri

GDR Neutrinos

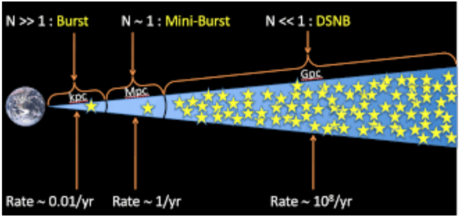
November 24, 2020

The Diffuse Supernova Neutrino Background

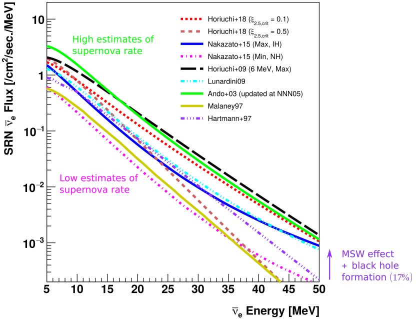
Neutrino flux from all distant core-collapse supernovae

2-3 galactic supernovae/century

1 SN/s in the observable Universe



J. Beacom



[Y. Ashida]

$$\Phi(E) = \frac{c}{H_0}\int_0^{z_{max}} R_{\mathsf{SN}}(z)\, F_\nu[E(1+z)]\,\frac{\mathrm{d}z}{\sqrt{\Omega_m(1+z)^3+\Omega_\Lambda}}$$

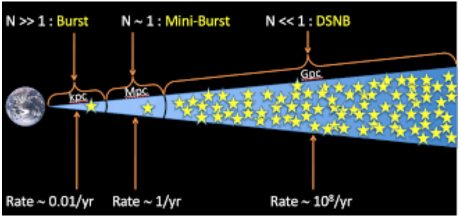
- Aggregate properties of core-collapse supernovae
- All flavors of neutrinos, redshifted
- Elusive low energy signal

The Diffuse Supernova Neutrino Background

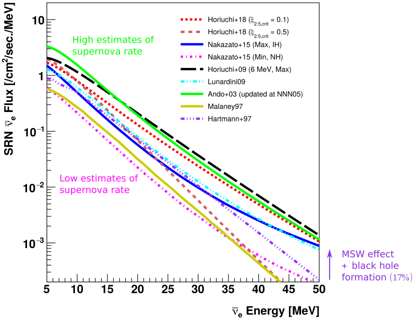
Neutrino flux from all distant core-collapse supernovae

2-3 galactic supernovae/century

1 SN/s in the observable Universe



J. Beacom

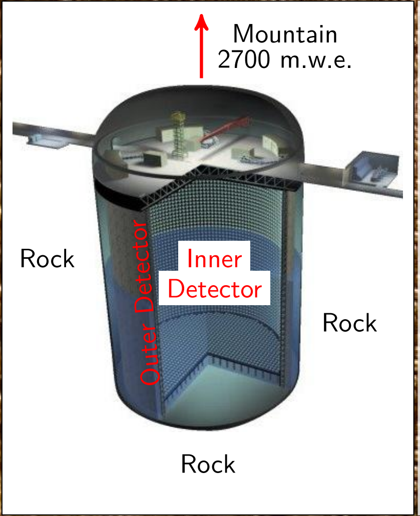


[Y. Ashida]

$$\Phi = \int \left[\nu \text{ emission (black hole fraction)} \right] \otimes \left[\text{Star formation} \right] \otimes \left[\text{Universe expansion} \right]$$

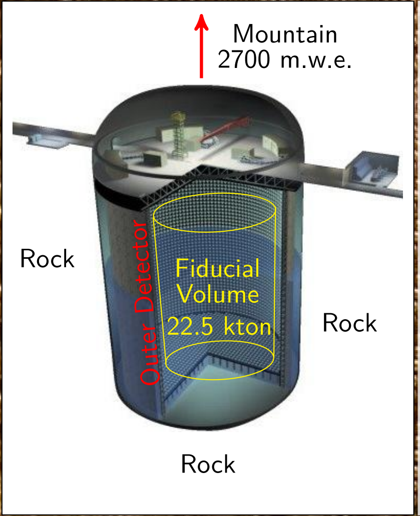
- Aggregate properties of core-collapse supernovae
- All flavors of neutrinos, redshifted
- Elusive low energy signal

Super-Kamiokande in a nutshell



- Kamioka Mine, Japan
- 50 kton Water Cherenkov detector
- Water constantly recirculated and purified
- 11129 Inner Detector PMTs
  50 cm, 3 ns resolution
- Energy coverage
  4 MeV to ∼TeV
- Currently in phase VI, doping with Gadolinium completed this summer
- Current study: phase IV
  longest data-taking period (2008-2017)
  2790.1 live days

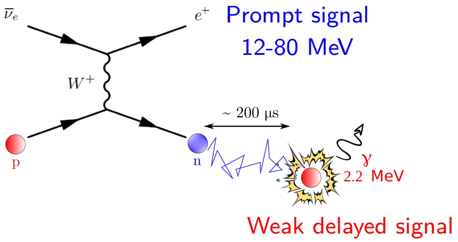
Super-Kamiokande in a nutshell

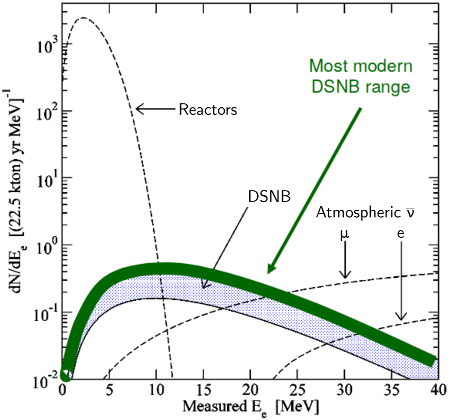


- Kamioka Mine, Japan
- 50 kton Water Cherenkov detector
- Water constantly recirculated and purified
- 11129 Inner Detector PMTs
  50 cm, 3 ns resolution
- Energy coverage
  4 MeV to $\sim$TeV
- Currently in phase VI, doping with Gadolinium completed this summer
- Current study: phase IV
  longest data-taking period (2008-2017)
  2790.1 live days

The DSNB in Super-Kamiokande

Detecting antineutrinos via Inverse Beta Decay (IBD)



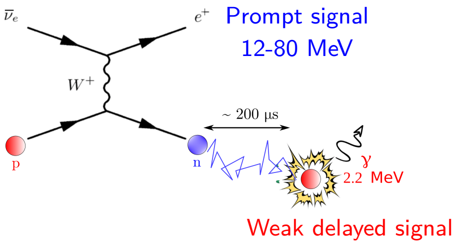


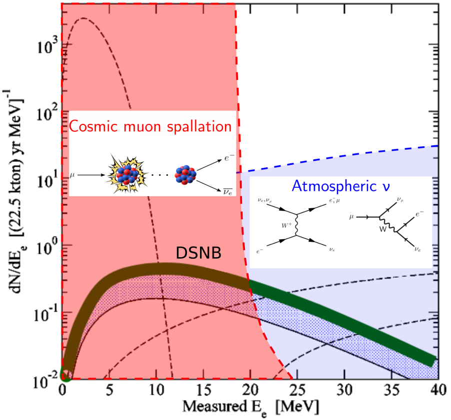
[Beacom and Vagins, Phys. Rev. Lett., 93:171101, 2004]

- 5-20 events/year – Energy range 12-80 MeV
- Need to characterize spallation and atmospheric backgrounds and **identify the neutrons**

The DSNB in Super-Kamiokande

Detecting antineutrinos via Inverse Beta Decay (IBD)





[Beacom and Vagins, Phys. Rev. Lett., 93:171101, 2004]

- 5-20 events/year – Energy range 12-80 MeV
- Need to characterize spallation and atmospheric backgrounds and **identify the neutrons**

The three pillars of the DSNB analysis

After basic noise reduction cuts:

I - Spallation cuts

- Remove radioactive isotopes produced by cosmic muons

II - Atmospheric background reduction/characterization

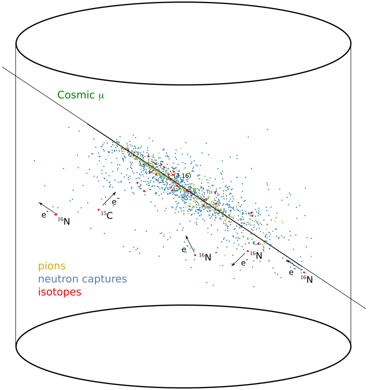
- Remove atmospheric signals with pions/muons/gammas
- Estimate spectral shapes of low energy atmospheric neutrinos

III - Neutron tagging

- Possible only since SK-IV
- Identify neutron capture signal in water

Spallation backgrounds

Radioactivity induced by cosmic muon spallation in water



[FLUKA simulation, A. Coffani]

- One spallation muon every two minutes
- Needs to be reduced by $\mathcal{O}(10^4)$
- Main signatures

  $> 99\%$ β decays: $A \to e^{\pm} + \nu$

  $< 1\%$ IBD-like (^{9}Li): $A \to e^{\pm} + n$
- Isotopes' half-lives up to 13 s

  $\Rightarrow$ correlations over large time scales
- No existing simulation in WC detectors

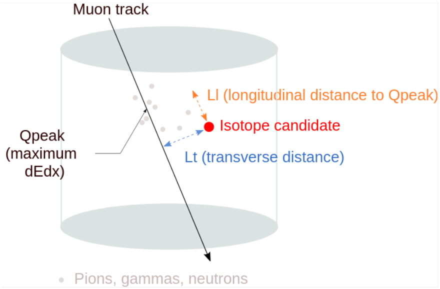
Reduction strategy:

- Identify isotope clusters and neutrons from muon showers
- Investigate correlations between muons and candidate events

Spallation: hunting for correlations

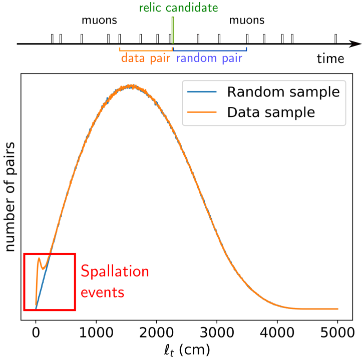
Pair each candidate event with muons up to 30 s before
Investigate correlations using a likelihood analysis

Observables



- Δt, L_t, L_l: distance and time difference
- resQ: charge deposited by the muon in addition to minimum ionization

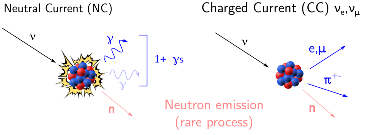
Extracting distributions



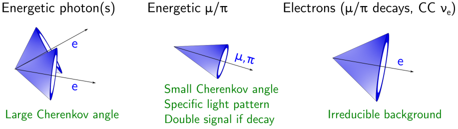
Final performance: $> 90\%$ background rejection ($> 99\%$ on ^{9}Li)
40-90% signal efficiency (depending on reconstructed energy)

Evaluating and reducing atmospheric neutrinos

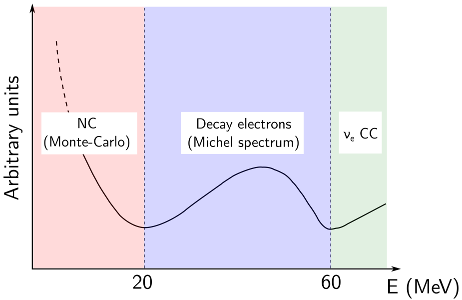
Interaction types



Light patterns in SK



Atmospheric backgrounds after cuts

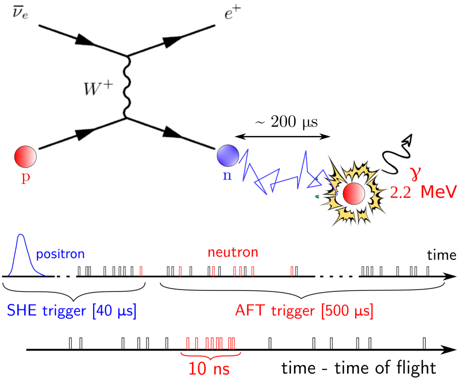


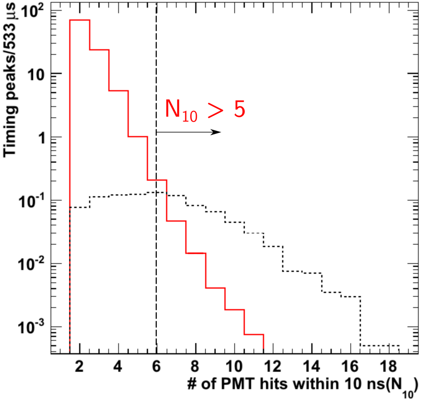
Estimating normalization and spectral shapes:

- $\mathcal{O}(100\%)$ uncertainties on rates and spectral shapes below 100 MeV except for decay electrons (measured Michel spectrum from stopping muons).
- Strategies: Use T2K to estimate cross-sections and efficiencies (NC backgrounds), or use sidebands in energy and Cherenkov angle. [Y. Ashida, Ph D. thesis (2019)]

Selecting neutrons: a needle in a haystack

Neutron capture occurs **near the positron vertex**

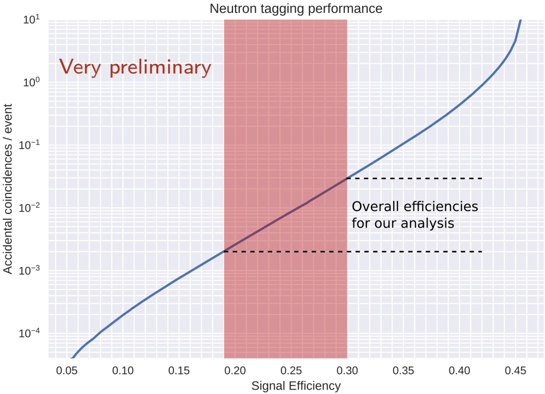




- New in SK-IV: "AFT" trigger window after the positron window
- Sensitivity to dark noise: inject random trigger data into MC simulation (SKDetSim – GEANT3) for cut optimization.
- Preselection: define **candidate neutron peaks** with $N_{10} > 5$

Selecting neutrons: final step

Use a Boosted Decision Tree (BDT) to tag neutron candidates.



[A. Giampaolo]

- **Final performance**: $0.2\% - 3\%$ background acceptance
  $18\% - 30\%$ signal efficiency.
- Expect $\times 4$ performance enhancement after Gadolinium doping.

Analysis procedures

Supernova model-independent analysis

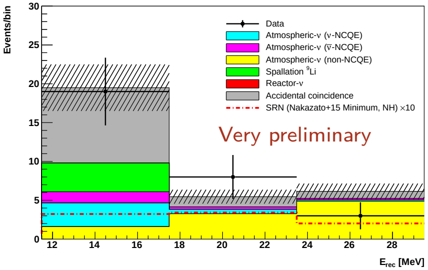
- Low energy analysis: $12 - 30$ MeV reconstructed positron energy
- Atmospheric CC: estimate by fitting Michel spectrum in $30 - 50$ MeV
- Atmospheric NC: estimate using T2K data $\Rightarrow$ define 3 large energy bins
  50% uncertainties for NC backgrounds – 30% uncertainties for CC
- Bin-by-bin cut optimization and limit calculation

Spectral analysis

- Fit observed energy spectrum by DSNB $+$ atmospheric spectra
- Need to eliminate spallation $+$ solar backgrounds
  $\Rightarrow 16 - 80$ MeV energy range
- Atmospheric spectral shapes: use sidebands in Cherenkov angle for NC and μ/π. Assume $\mathcal{O}(100\%)$ uncertainties on normalizations and shapes **except for Michel spectrum**.

Supernova model-independent analysis

Flux limits close to optimistic DSNB models at high energy



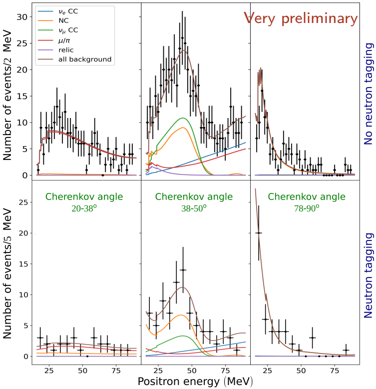
Search Results & Integrated SRN Electron Antineutrino Flux [/cm²/sec.]

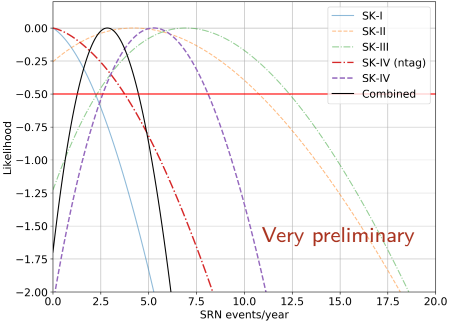
E_ν region [MeV]	13.3–19.3	19.3–25.3	25.3–31.3
SK-IV 2970 days (Expected)	**9.48**	**1.35**	**0.82**
SK-IV 2970 days (Observed)	**9.08**	**2.22**	**0.35**
Nakazato+15 (Minimum, NH)	0.337	0.089	0.026
Horiuchi+09 (6 MeV, Maximum)	2.534	0.887	0.314
Ando+03 (updated at NNN05)	2.652	0.796	0.261

- Neutron tagging: $16 \longrightarrow 12$ MeV analysis threshold
- Important uncertainties from NC γ emission and neutron multiplicity

Spectral analysis

Combination of SK-I to IV for an optimistic SRN model [Ando 03]





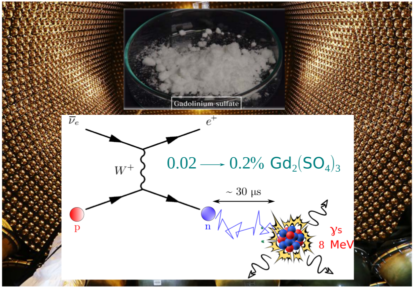
- Slight excess at low energy without neutron tagging
- Combined 90% C.L. limit: 2.7 cm^{-2}.s^{-1} (predicted: 1.7 cm^{-2}.s^{-1})

The DSNB models are getting tantalizingly close...

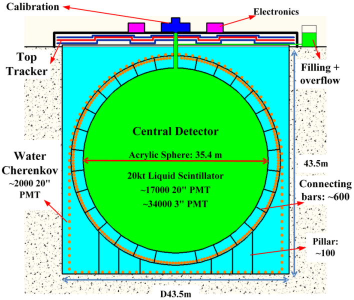
The near future: Super-K Gd and JUNO

Next 10 years: Identify IBD neutrons by enhancing the capture signal

Super-K Gd (just started!)



JUNO (2022)

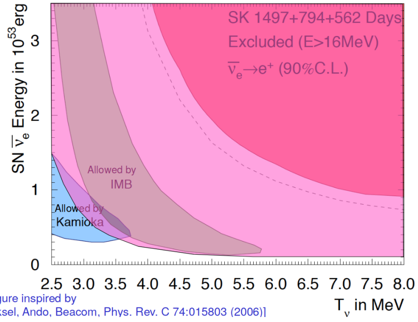


- Super-K Gd and JUNO will probe most of the DSNB parameter space!
- No spectral characterization: lack of statistics
  Atmospheric NC becomes the dominant background (large systematics)

The near future: Super-K Gd and JUNO

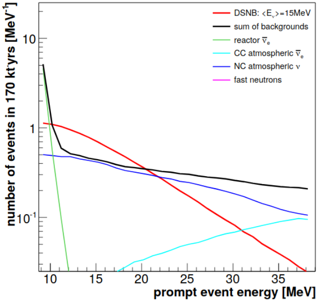
Next 10 years: Identify IBD neutrons by enhancing the capture signal

Super-K Gd (just started!)



[Figure inspired by Yuksel, Ando, Beacom, Phys. Rev. C 74:015803 (2006)]

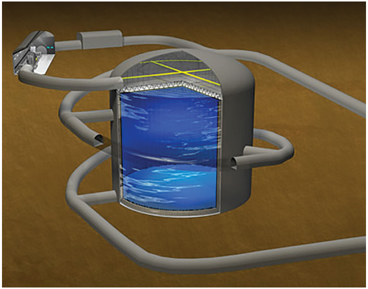
JUNO (2022)

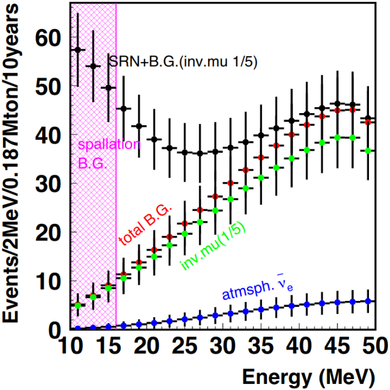


- Super-K Gd and JUNO will probe most of the DSNB parameter space!
- No spectral characterization: lack of statistics
  Atmospheric NC becomes the dominant background (large systematics)

Beyond a discovery: Hyper-Kamiokande

Hyper-Kamiokande will allow in-depth studies of the DSNB spectrum



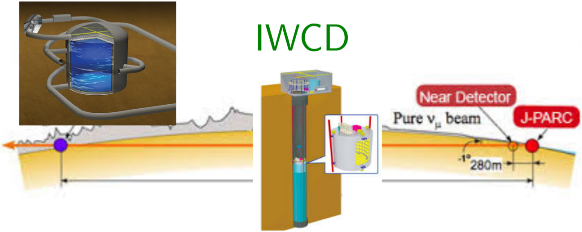


187 kton $= 10\times$ SK fiducial volume

$2\times$ PMT quantum efficiency

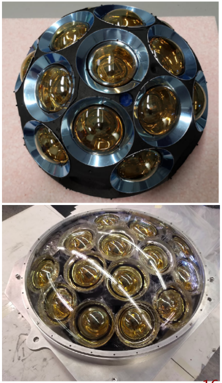
- First analysis of the tail of the DSNB spectrum
- Limits on the fraction of supernovae forming black holes
  Combined studies with LSST to limit the supernova rate

Hyper-Kamiokande: going further



Opening the low energy region:

- IWCD's cross-section studies
  - ⇒ Characterize neutrino-nucleus interactions
  - ⇒ Reduce atmospheric neutrino systematics
- Use of multi-PMTs
  - ⇒ Improve vertex resolution?
  - ⇒ Impact on neutron tagging?
- Doping HK with gadolinium?



Conclusion

- Current limits in Super-Kamiokande: first analysis of the diffuse supernova neutrino background with the full SK-IV dataset **and neutron tagging capabilities**.
- The most optimistic DSNB models are within a factor of two of the current limits...maybe a discovery in Super-K Gd or JUNO?
- Spectral characterizations and studies of astrophysical parameters will be made possible in Hyper-Kamiokande
- Combined studies with neutrino beams and telescopes will be essential

Stay tuned for the near and far future!

Thank you for your attention